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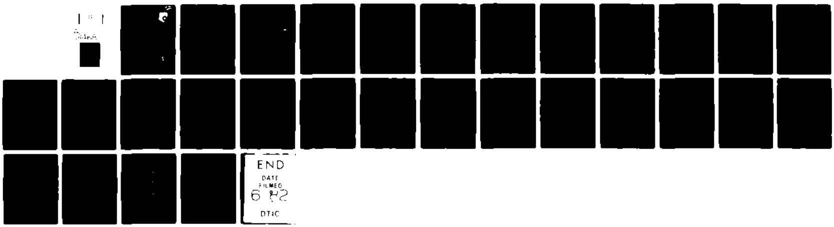

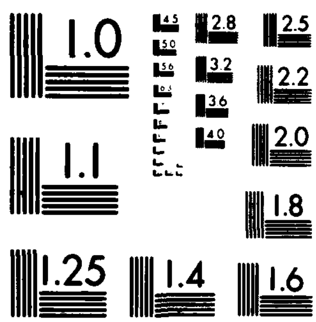


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# MEASUREMENT OF MATERIAL PROPERTIES FOR HIGH RATE DEFORMATION PROCESSES

Dr. Ted Nicholas
Metals Behavior Branch
Metals and Ceramics Division



February 1982

Report for Period 1 June 1981 - 1 November 1981

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As higher and higher strain rates are achieved in experiments, the deformation field varies from one which is nearly homogeneous to the case where high amplitude stress waves or shock waves are propagating. In order to analyze a high rate experiment, a sound mathematical theory of wave propagation is required. This, in turn, requires a description of the material behavior. But it is this description of material behavior which is being sought in the first place. It is this dilemma which has caused problems

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(ABSTRACT CONT.)

in deducing the dynamic properties of materials at very high strain rates.

Techniques available for determining the high rate properties of materials are reviewed. These range from split Hopkinson bar, in which a uniaxial stress state is assumed, to the flat plate impact experiment where waves of uniaxial strain occur. Other configurations include expanding rings and cylinders and skew plate impacts. These various techniques are discussed with respect to their fundamental limitations and the type of material property data which can be obtained.

## FOREWORD

This technical report was prepared by the Metals Bahavior Branch, Metals and Ceramics Division, Materials Laboratory, Air Force Wright Aeronautical Laboratories. The work was performed by Dr. T. Nicholas, (AFWAL/MLLN) under in-house Project No. 2307P1. The report covers work conducted from June 1981 to December 1981, and was submitted by the author in December 1981.

This report was presented at the Physics of Explosives Technical Meeting at Lawrence Livermore National Laboratory, California on 21-23 October 1981 which was held under the auspices of data exchange agreement DEA-AF-F/G-7304. This report is also being published as part of the classified conference proceedings.

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# SECTION I

# INTRODUCTION

Interest in high rate deformation processes in the Department of Defense is concerned with the phenomenology of the formation of rod-like impact devices or fragments and their subsequent interaction with targets such as armor plates. A recent study by the National Materials Advisory Board on "Material Response to Ultra-High Loading Rates" presents a summary of the state of the art as well as recommendations for future research in the areas of material properties (Reference 1). The study, as is this report, concerns itself with high velocity ordnance problems involving shaped-charge jets, self-forging projectiles, and fragmentation devices as well as their interaction with armor targets. In each case, the material behavior involves high rate of strain, large deformation, high pressures, and high temperatures due to adiabatic heating in both the projectile and the target. The extreme complexity of the problem does not lend itself to closed-form or even approximate mathematical analyses. Furthermore, limited information is available on material behavior under this wide range of conditions. Thus, ordnance development has proceeded along mainly empirical paths for many years.

Within the last decade, the development of highly sophisticated two- and three-dimensional computer codes for impact problems as well as major improvements in computer hardware have led to the increasing use of numerical methods for evaluating complex impact phenomena. Finite-difference and finite-element techniques have been applied in a number of situations to analyze the complex stress and strain states in both projectile formation and target interaction. As pointed out by the National Materials Advisory Board (NMAB) report, the most fruitful course for advanced ordnance development appears to be an iterative combination of ballistic test firings, numerical simulations with computer codes, and dynamic material property determinations. The most limiting aspects of this procedure are the lack of availability of reliable material property information under the conditions of interest and the lack of a straightforward approach for determining these properties. This report will discuss some of the

techniques for obtaining dynamic material property information from laboratory tests as well as the assumptions and limitations of those tests.

# SECTION II

# BACKGROUND

The increased capability of computer codes has provided additional analytical capability for terminal ballistics and ordnance problems while simultaneously generating increasing demands for accurate representation of the dynamic properties of materials. Since the discretization methods treat only the laws of physics (conservation equations), geometry and initial conditions, and material description, any failure to model a physical process with a computer code is generally attributed to inadequacy of the material model, assuming the numerical procedures are properly carried out. Thus, historically, many aspects of material behavior have been inferred from numerical computations of highly complex phenomena and comparisons with experimental observations or measurements. This indirect method of deducing material properties such as dynamic yield strength can often be misleading, particularly when different values are obtained for different experimental configurations. Since dynamic material property data are not widely available, nor are there any individual tests from which to obtain these data, little attention has been given by code users to the application of sophisticated constitutive relations for the description of the material. Thus, few codes bother with strain rate effects, strain hardening, or pressure dependence of yield and flow stresses.

The formulation of material behavior in a typical computer code involves the decomposition of the stresses and strains into their hydrostatic and deviatoric components which are assumed independent (Reference 2). The hydrostatic components are related through an equation of state which relates the pressure, density, and internal energy of the material. Some variant of the Mie-Gruneisen equation of state is commonly used in many codes except at very high pressures such as those encountered in hypervelocity impact problems. It is important to note that most formulations readily compute internal energy, but the determination of temperature is not a straightforward process. The deviatoric strains are further decomposed into elastic and plastic components with the

restriction of incompressibility being imposed on the plastic strains. It should be noted that the decomposition into additive elastic and plastic components is valid only for small strains less than approximately 0.3. It should also be noted that the strain displacement relations used in most codes includes only the linear terms in the displacement gradient and thus represents small strain and rotation behavior. The plastic strains are treated using some of yield condition and flow law, typically a von Mises yield criterion and a Prandtl-Reuss incremental flow law. In some formulations, strain rate or strain hardening are introduced into the yield condition. Through this formulation, yield and flow stresses are totally independent of the hydrostatic components of stress and strain. There is some evidence to indicate that this assumption is not valid although this issue has not been resolved to date.

As noted in the NMAB report cited previously, shaped-charge jets, self-forging fragments and fragmentation devices can generate peak pressures upon impact from 30 to 200 GPa, or average values ranging from 2 to 20 GPa. Average temperature can range from 0.2 to 0.5 of the melting temperature, with peak temperature approaching melt and even exceeding it in the case of shaped-charge jets. In the formation phase of these projectiles, maximum strains can range from 1 (100 percent strain) to greater than 10 for shaped-charged jets. Average strain rates are of the order of $10^4$ to $10^5$ $S^{-1}$ with peak values of $10^6$ to $10^7$ $S^{-1}$. Similar values of strain and strain rate may be encountered in target response to these various impact devices. In addition to modeling material behavior, failure criteria represent an important aspect of most problems. Failure models in most codes tend to be quite simple because of the lack of data and models to represent this highly complex dynamic failure process. In this report, attention will be paid only to the determination of the constitutive behavior of materials, primarily metals. It should be kept in mind, however, that information on material failure could be extracted from most of the tests discussed.

# SECTION III

# TEST TECHNIQUES

One general type of experiment for determining material properties at high rates of strain which is both amenable to mathematical analysis and relatively simple to perform is depicted in Figure 1. The geometrical configuration is a right circular cylinder whose axis in in the x-direction subjected to a constant velocity at one end at time t = 0. The velocity could be in a direction to produce either tension or compression. It represents the boundary condition which would be realized if a rod or plate was impacted against another stationary rod or plate of identical material and geometry at a velocity of $2V_0$. The relative dimensions of the specimen in Figure 1 are neither specified nor limited. It could represent a long slender rod (as shown) or a short plate of large diameter. For assumed elastic material behavior, the strain-time profile at some position $\xi = x/l$ along the rod is shown in Figure 2. The solution also assumes that the boundary condition of a constant velocity at the free end is applied instantaneously, i.e., there is zero rise time in the applied velocity. Under these assumptions, the strain-time profile is seen to consist of a number of steps in strain, each corresponding to the passage of an elastic stress wave moving back and forth across the specimen. In using this type of experiment for determining dynamic material properties we generally deal with the two extremes of the conditions depicted in Figures 1 and 2. In the first case, we consider high velocity impacts where we observe the propagation characteristics of only a single high amplitude stress wave through the sample, i.e., a wave propagation experiment. In the second case, we deal with impact velocities and specimen geometries where many wave reflections take place during the course of the experiment so that we can deal with <u>average</u> values of stress and strain and do not have to consider the details or nature of the wave propagation in the material. The idealized solution of Figure 2 assumes elastic behavior and instantaneously applied velocity whereas in an actual experiment, these assumptions are generally violated because of the inability to achieve perfect impacts experimentally and because material behavior is generally inelastic at high impact velocities.

The general dynamic material property experiment can be broken into two broad classes, those involving uniaxial stress and those involving uniaxial strain. The uniaxial stress experiments involve rods or cylinders having diameters which are small compared to the wavelength of propagating disturbances such that radial inertia and stresses transverse to the propagation direction can be ignored. Uniaxial strain experiments involve plates with large diameters such that observations along the centerline of the plate are not affected by unloading waves from the outer diameter. In this latter configuration, strains in the direction transverse to the propagating wave are identically zero.

The subject of dynamic test techniques and material properties has been treated extensively in the literature. As higher and higher strain rates are attempted, the experiments go from states of uniaxial stress to uniaxial strain. Additionally, thermodynamic considerations become more important as higher rates are achieved because conditions change from essentially isothermal to adiabatic at the highest rates. Finally, as higher and higher rates are achieved, wave propagation effects become increasingly important. The important considerations in dynamic testing are summarized in chart form in Figure 3. Techniques for testing materials at high rates of strain are reviewed in Reference 3 and a general discussion of material behavior at high strain rates can be found in Reference 4.

## 1. WAVE PROPAGATION EXPERIMENTS

The plate impact experiment which involves a state of uniaxial strain is one of the most widely used configurations for studying material behavior under high velocity impact conditions. The experiment is discussed in detail in many publications (see, for example, Karnes (Reference 5) and has been used primarily for determining the high pressure equation of state of materials. Less emphasis has been placed on this experiment for extracting information regarding plasticity effects or strain-rate effects. Since this is a wave propagation experiment, there is no direct method for extracting information on material properties. Rather, one must assume something about the form of the material behavior

because in order to conduct an analysis of a propagating wave, one must have a description of the material behavior. Yet it is this material behavior which is being sought in the first place. Thus, in performing wave progagation experiments to determine dynamic material properties, one can get at most either verification of a proposed material model or the best values of constants in a particular form of material model. In plate impact experiments, there has been a considerable amount of work in determining the uniaxial strain stress-strain relation assuming that the material model consists of a single-valued relation between stress and strain deviators for conditions where no unloading occurs. This curve can often lie above the curve determined solely from quasi-static uniaxial stress data, yet the model is still "rate-independent." This can probably be attributed to the fact that wave profiles are relatively insensitive to the form of the constitutive model and can be readily predicted from any model which provides reasonable values of stress at the average strain rates occurring in a particular experiment. For another experiment, however, which involves a different range of strain rates, a different dynamic stress-strain curve may be required to predict the wave profiles. Figure 4 from Barker et al (Reference 6) illustrates the degree of rate dependence for aluminum alloy 6061-T6. The uniaxial strain curve determined from quasi-static tensile data is seen to lie below the curves for individual impact experiments. Each curve for a particular experiment is determined by assuming a rate-independent material model. Note that no single curve fits all of the dynamic data, but all the data lie above the quasi-static prediction.

Particular characteristics of waves propagating in plate impact experiments may be utilized to deduce material plasticity effects in addition to providing information on the equation of state (Reference 7). The thermodynamic equation of state describes material behavior at very high pressures. For very high velocity impacts, one can generate shock fronts propagating through the plate. The locus of pressure-density states that are attainable from a single initial state through the application of the well-known jump conditions across a shock front is referred to as the Hugoniot or Rankine-Hugoniot curve or equation of

state. It is based on the assumptions that the experiment is purely one-dimensional (uniaxial strain), thermal equilibrium is rapidly obtained behind the shock front, the shock wave is steady so that the jump conditions may be applied, and the stress state is purely hydrostatic, i.e., yield stress can be neglected in comparison with the hydrostatic stress level. As lower pressures are obtained, the stress state is no longer hydrostatic. A yield condition must be considered for the deviatoric stresses along with a flow law. The stress-strain curve for an assumed strain-rate independent elastic perfectly plastic material is shown schematically in Figure 5 for both uniaxial strain and uniaxial stress. The material behavior in a plate impact experiment (uniaxial strain) is seen to differ from the idealized Hugoniot by $2Y_0/3$ where $Y_0$ is the yield stress in a uniaxial stress tension test. It can be seen that for high pressures, the differences between these two curves could be very slight (Figure 4). It is therefore difficult to deduce much information on plasticity or strain-rate effects in this situation. If an unloading curve were included, it would lie an equal distance below the Hugoniot. A thin plate impact in such material at low pressures gives rise to the idealized wave profile shown in Figure 6. In this general case, both elastic and plastic wave fronts occur for the unloading wave as well as for the loading wave. If the individual loading wave fronts can be distinguished experimentally, information can be obtained on dynamic plastic effects in metals from the various features of the propagating wave fronts, provided that the pressure levels are low enough to be able to distinguish the differences due to plasticity effects. Measurements of the amplitude of the Hugoniot elastic limit, for example, provide information of the dynamic yield stress when the elastic wave precursor is distinct from the propagating plastic wave. This dynamic yield strength is influenced, however, by both pressure and temperature generated by adiabatic heating. Although the conventional formulation of material models ignores the effect of pressure on yield strength, there is some evidence that indicates flow stress increases with pressure. It is difficult to distinguish between effects of pressure and temperature and strain rate on yield stress because higher strain rates are generally obtained in experiments involving higher impact velocities and, hence, higher pressures. Information regarding strain-rate effects can also be

obtained from this plate experiment through observation of the rate of decay of the elastic precursor. A thorough review of the work in shock compression of solids is given by Davison and Graham (Reference 8).

If a very thin plate or short time explosive is used to generate the stress wave in plate impact experiment, information is obtainable by observation of both loading and unloading waves. Measurements of the amplitude of the unloading elastic wave, when it can be clearly identified, provides information on the plastic flow stress in a previously dynamically compressed or shocked material. The thin plate impact experiment and resulting wave profile observations has been suggested as a method for verifying assumed stress-strain behavior by Herrmann and Lawrence (Reference 9). In a series of numerical calculations of wave profiles in materials described by several constitutive models, they have shown that peak stress attenuation is critically dependent on the assumed value of the yield stress even when the yield stress is only one or two percent of the initial peak stress. They have also concluded that rate-dependent plasticity is necessary to fit the details of experimentally observed wave profiles in metals while details of strain hardening and Bauschinger effects are generally less important.

A condiderable amount of research has been concerned with the study of plastic waves propagating in long rods. In this situation, the stress state is assumed to be uniaxial and radial inertia effects are assumed negligible. This assumption is generally violated in the vicinity of the impact end where the highest strain rates are achieved. At distances greater than several bar diameters from the impact end, the strain rates generally do not exceed several hundred $sec^{-1}$. Most of the work in plastic wave propagation can be broken up into three categories of material models; 1) a rate-independent model based on the quasi-static stress-strain curve, 2) a rate-independent model based on a single "dynamic" stress-strain curve which is different than the quasi-static curve, and 3) a strain-rate-dependent mode. These models and the experimental work to determine them are discussed in detail by Nicholas (Reference 10). In general, it can be concluded that plastic wave propagation experiments in long rods provide little information on dynamic

properties because of the relatively small rate sensitivity of most metals at the strain rates obtained in these experiments and the relative insensitivity of wave profiles and velocities to the constitutive model.

## 2. EXPERIMENTS INVOLVING AVERAGE STRESSES AND STRAINS

The most popular experiment for determining dynamic properties of materials under uniform stress and strain conditions in small specimens is the split Hopkinson pressure bar or Kolsky apparatus (Reference 11). The apparatus is described by Lindholm (Reference 12), among others, and a discussion of various modifications and uses of the apparatus can be found in the article by Nicholas (Reference 4). The underlying principle, due to Hopkinson (Reference 13), is what occurs at the ends of the specimen sandwiched between two long elastic bars can be determined from observations of the stress waves propagating down the bars and recorded using strain gages. It is assumed that the elastic waves propagate at constant velocity in an undispersed manner in the Hopkinson bars, an assumption which is valid for wavelengths exceeding the bar diameter. The condition which must be met to obtain valid information from a split Hopkinson bar test is that the stresses at both ends of the specimen are essentially identical at any instant of time. This means that a large number of stress waves must be propagating back and forth in the specimen in order to have a valid test. As higher and higher strain rates are attempted, the amplitude of the propagating waves increase and the number of wave reflections decrease eventually violating the basic assumptions (Figure 2). When different values of stress occur at the two ends of the specimen because of wave propagation phenomena, the assumptions of uniform or average stresses and strains are invalid and the test provides invalid data. Furthermore, at higher and higher strain rates, the assumption of a state of uniaxial stress in the specimen and the neglect of radial inertia, radial shear, and end friction all tend to become invalid. Thus, there are fundamental limitations to the strain rates which can be achieved with this technique. Strain rates in compression up to $10^4$ $sec^{-1}$ can be achieved in carefully performed tests, and rates up to $10^5$ $sec^{-1}$ have been documented using extremely small specimens for some materials. At these very high rates, however, conflicting results have been reported leading

one to question whether all of the assumptions for the conduct of the test have been met satisfactorily.

A variation of the standard Hopkinson bar test involves removing the input bar and impacting the specimen directly with a striker bar (Reference 14). In this situation, direct measurement of strain must be made on the specimen. Although higher rates can be achieved with this technique, the same fundamental questions about the validity of the experiment must be asked as in the split Hopkinson bar experiment.

An alternative version of the compression split Hopkinson bar technique has been developed for testing in a state of uniaxial strain (Reference 15). In this configuration, large diameter bars are used to compress a short flat plate whose diameter is large compared to its length. In addition, a rigid confining ring is placed around the specimen to try to prevent radial expansion. If the ring were truly rigid and fit perfectly over the specimen, a state of uniaxial strain (no lateral deformation) could be achieved. In an actual experiment, perfect rigidity and tolerances are difficult to achieve. Another difficulty is finding material which has a yield strength in uniaxial stress for the Hopkinson bars which is great enough to apply forces to a specimen being deformed in uniaxial strain where high hydrostatic stresses may be present.

The split Hopkinson bar has also been modified for use in tension, torsion, and shear as discussed in (Reference 4). A schematic showing the specimen configurations for compression, shear, and tensile testing is presented in Figure 7. Torsion testing has been performed in several laboratories using thin-walled tubular specimens bonded to the torsional Hopkinson bars. An alternative version of the tensile Hopkinson bar was developed by Nicholas (Reference 16) in which a compression pulse is reflected off the free end of the Hopkinson bar to develop a tensile pulse. The specimen is protected from the compression pulse by a collar which cannot sustain tensile loading. The tensile version of the test can be further modified by utilizing a notched specimen. The notch serves to localize the strain in the specimen, thereby increasing the local

strain rate, while simultaneously creating a state of confined triaxial tension. With a detailed analysis of the three-dimensional stress state, this technique has the demonstrated capability for extending the strain-rate regime available in dynamic tensile testing.

## 3. OTHER TECHNIQUES

Among the other techniques available for evaluating dynamic material properties is the Taylor cyclinder experiment (Reference 17). In this test, depicted in Figure 8, a right circular cylinder is impacted against a rigid wall at a velocity V. A plastic wave is set up which propagates back from the wall, eventually stopping, and leaving a final deformed shape as shown in Figure 8b. Measurements of the undeformed length H and final $l_1$, along with a knowledge of the impact velocity, are all that is required to determine the dynamic yield strength in compression from some simple formulae. The derivation is based on a number of simplifying assumptions including those of a constant plastic wave speed and one-dimensional state of stress. Two-dimensional computer code modeling of this experiment has led to conflicting conclusions regarding the validity of the assumptions and the accuracy of the data obtained from the simple formulae. It is recommended that the Taylor cylinder experiment be used in conjunction with a finite-element or finite-difference wave propagation analysis before conclusions are drawn regarding dynamic yield strength unless only crude information is required. Because of the simplicity of the experiment, its use should provide significant useful information, particularly if conducted with instrumentation which can provide transient profiles of the deforming cylinder. In this situation, it is another version of a wave propagation experiment where material properties can be inferred through an iterative procedure.

An experiment which can provide high-rate tensile stress-strain data under uniform stress and strain conditions is the expanding ring or cylinder (Reference 18). In this test, a thin ring or cylinder is impulsively loaded from the center and deforms symmetrically in the radial direction. If the impulsive load is of very short time duration, the ring will decelerate due to the uniform tensile hoop stresses. Using

the F = ma equation of elementary physics, all that is needed is a measure of radial displacement to determine hoop strain and the second derivative of that displacement to determine the (negative) acceleration. The problem which has plagued this experiment over the years is the inability to determine the deceleration accurately. All attempts to double differentiate the most accurate radial displacement measurements have resulted in very poor accuracy in determining stress. Recent investigations using accurate velocity measuring devices indicate that sufficient accuracy may be obtained for stress values because only a single differentiation is needed. This approach opens the possibility for using the expanding ring or cylinder to obtain meaningful data at high rates of strain in tension.

Another technique developed recently is a one-dimensional wave propagation experiment involving the skew impact of flat plates (Reference 19). In this configuration, both pressure and shear waves are generated. The advantage of this technique over normal plate-impact experiments for developing constitutive equations is that the longitudinal wave profiles are less sensitive to the dynamic flow characteristics than transverse wave profiles because of the strong influence of the hydrostatic pressure on the longitudinal wave profile. An extension of this technique which involves the use of a thin-plate specimen sandwiched between two hard, high-impedance elastic plates has been suggested as a method for generating data at strain rates of the order of $10^5$ $sec^{-1}$ under states of combined pressure and shear (Reference 21). The configuration is based on the split Hopkinson bar concept involving average stresses and strains in a thin specimen. In this case, a biaxial stress state of combined pressure and shear is generated from the skew impact of a driver plate. Since the longitudinal wave arrives first, it builds up a state of hydrostatic pressure after which the slower shear wave subjects the specimen to plastic flow. Elastic wave analysis coupled with free-surface normal and transverse velocity measurements provide sufficient data to determine the high strain rate response of metals in shear under superimposed confining pressure. This technique holds great promise for providing data in combined stress states at high strain rates which have heretofore been unobtainable.

# SECTION IV

# CONCLUSIONS

Test techniques are available for determining properties of materials at high rates of strain under a variety of loading conditions and test geometries. Uniaxial stress states up to strain rates of the order of $10^4$ $sec^{-1}$ are obtainable using the split Hopkinson bar apparatus. Higher strain rates usually involve stress states involving some degree of lateral confinement and hence superimposed hydrostatic stresses. The highest strain rates are obtained when high amplitude shock waves propagate through the material. As higher and higher strain rates are achieved, wave propagation phenomena become more important and eventually dominate the conditions. Since there is no direct method for determining material properties from a wave propagation experiment, an indirect or iterative procedure must be used. This, in turn, can result in constitutive models which, although matching the experimental data, are not necessarily unique. Recent developments in test techniques and instrumentation hold promise for expanding the range of strain rates and stress states for which we can hope to accumulate data and increase our understanding of the behavior of materials under dynamic loading conditions.

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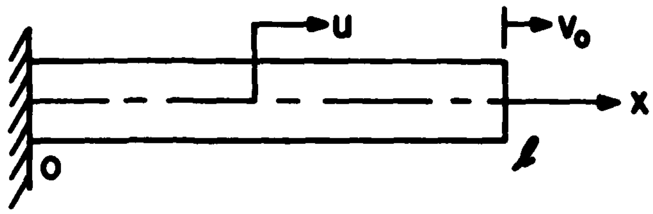


Figure 1. Uniaxial Tensile Test Configuration.

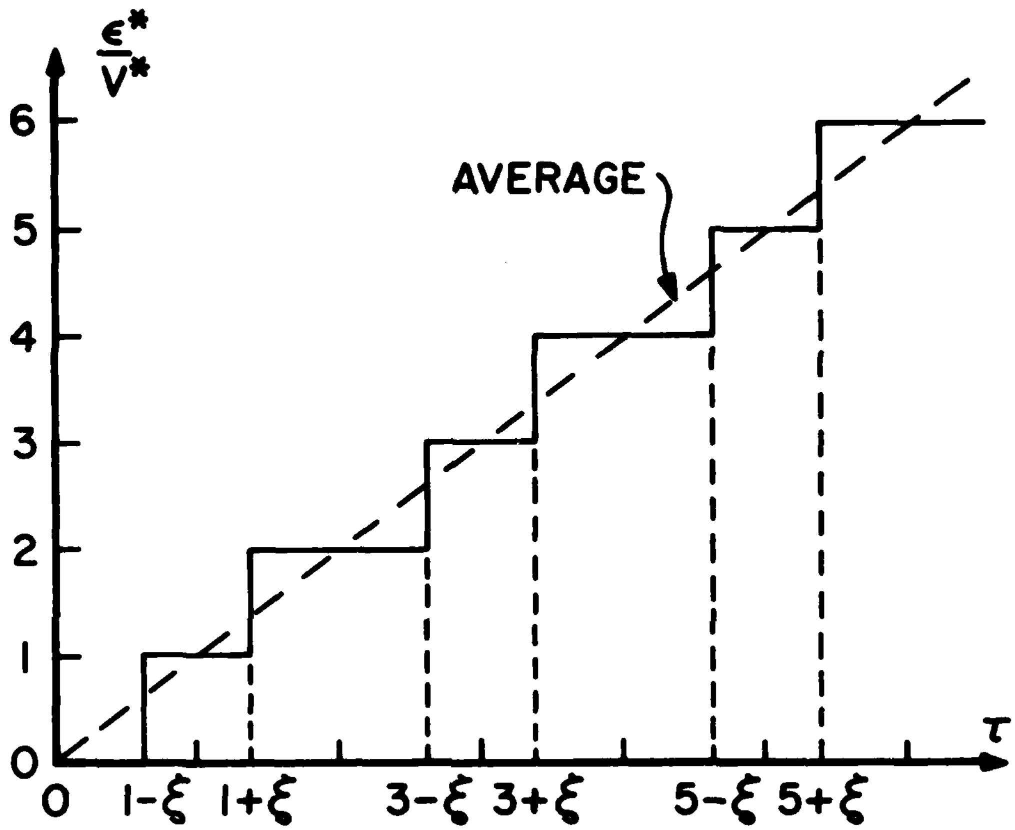


Figure 2. Non-dimensional Strain-time History for an Elastic Bar Subjected to a Step Input in Velocity.

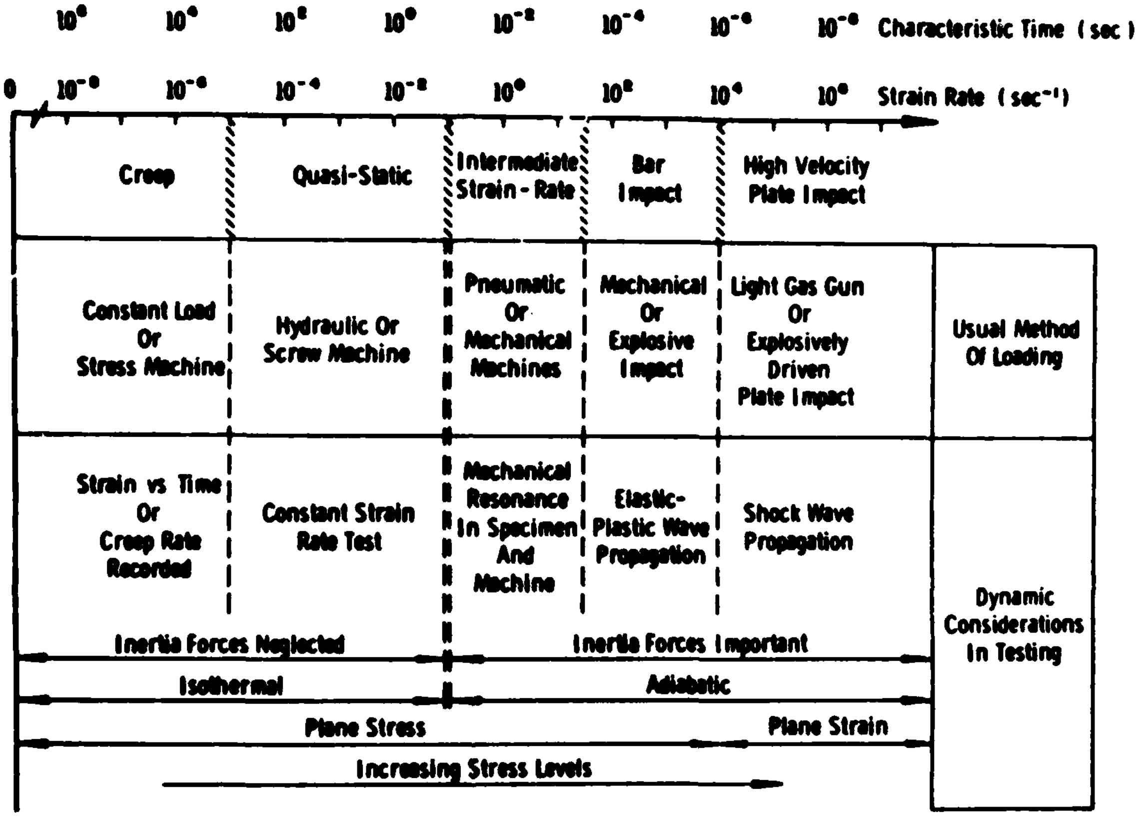


Figure 3. Considerations in Dynamic Testing From Reference 3.

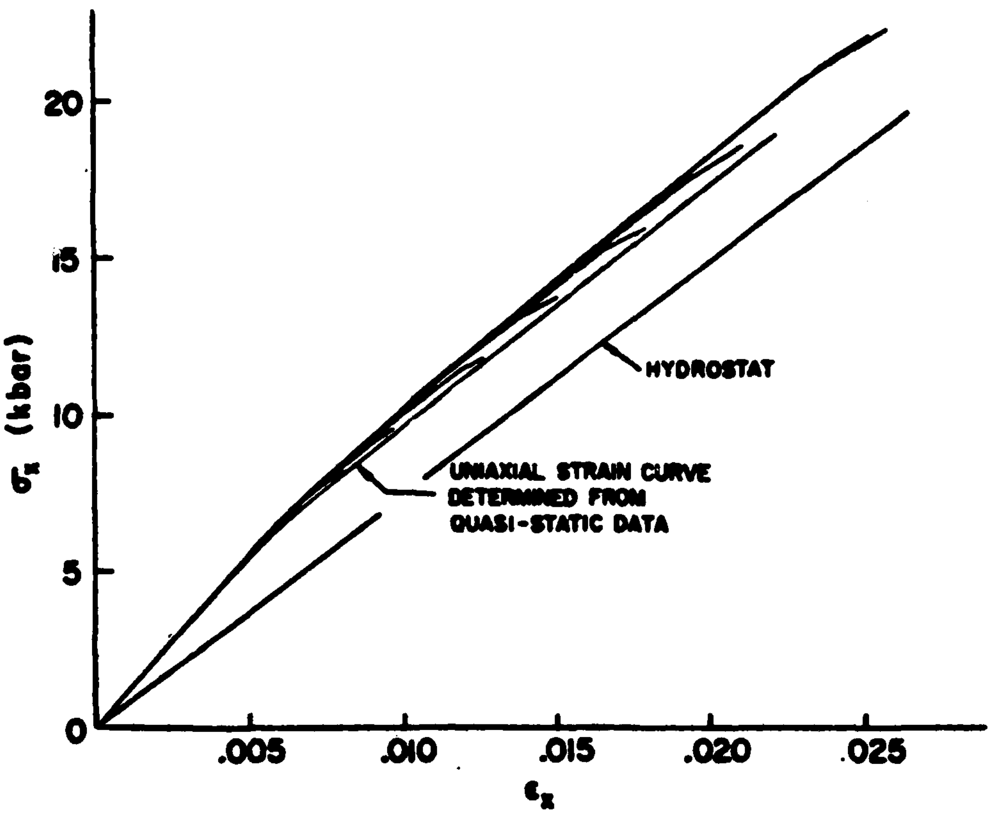


Figure 4. Dynamic Stress-strain Curves for 6061-T6 Aluminum from Plate Impact Experiments (from Reference 6).

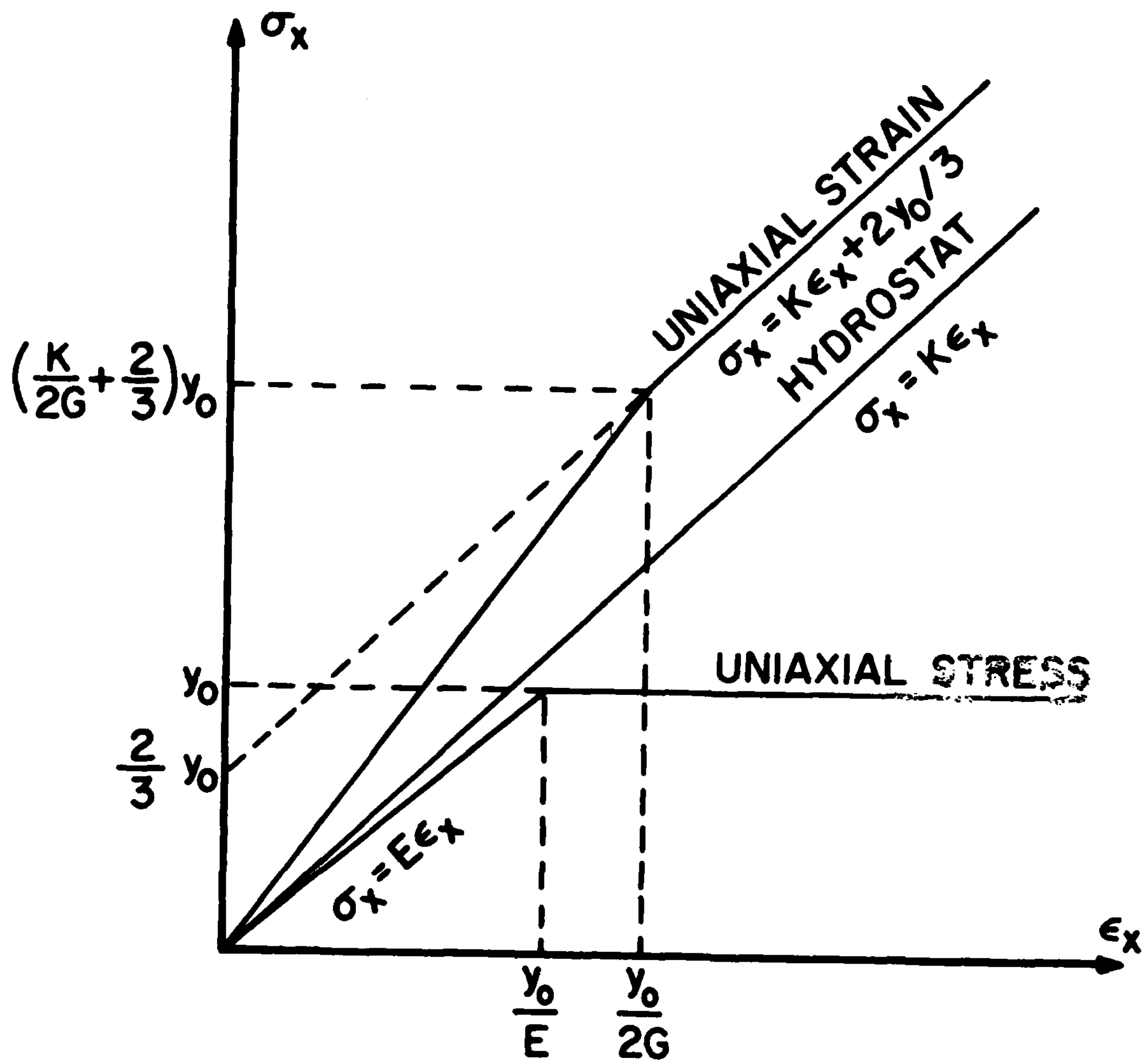


Figure 5. Stress-strain Behavior for an Elastic-perfectly Plastic Material in Uniaxial Stress and Uniaxial Strain.

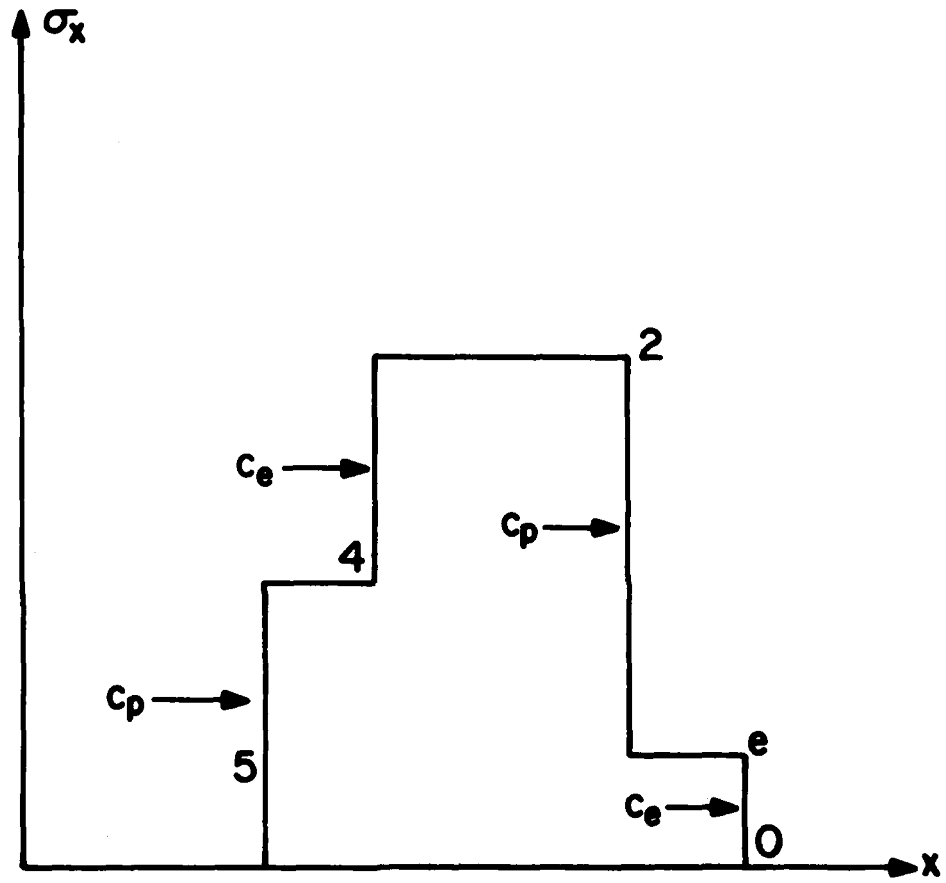


Figure 6. Schematic of Propagating Shock Wave Profile in an Elastic-Perfectly Plastic Medium Showing Both Loading and Unloading Waves Fronts.

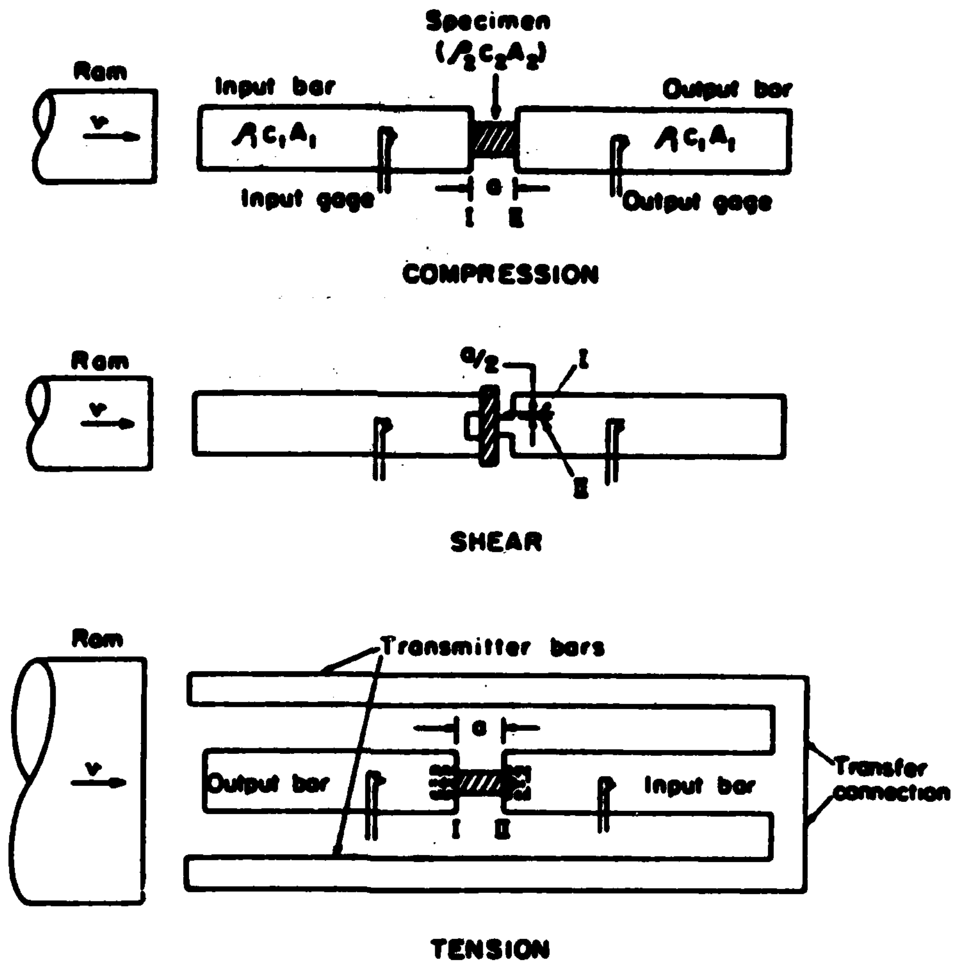


Figure 7. Schematic of Configurations for Compression, Shear, and Tensile Testing Using a Split Hopkinson Bar (from Hauser, F.E., Exp. Mech., 6, 395,1966).

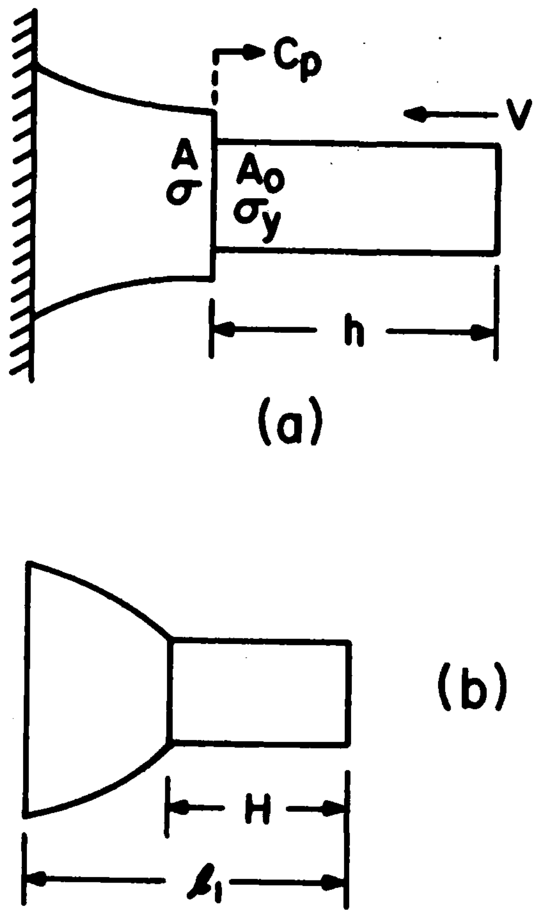


Figure 8. Schematic of Taylor Test; a) During Formation b) Final Deformed Shape.

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